Estimating national and local low-voltage grid capacity for residential solar photovoltaic in Sweden, UK and Germany

Citation for the original published paper (version of record):
Hartvigsson, E., Odenberger, M., Chen, P. et al (2021). Estimating national and local low-voltage grid capacity for residential solar photovoltaic in
Sweden, UK and Germany. Renewable Energy, 171: 915-926.
http://dx.doi.org/10.1016/j.renene.2021.02.073

(article starts on next page)

Renewable Energy 171 (2021) 915–926

Contents lists available at ScienceDirect

Renewable Energy

journal homepage: www.elsevier.com/locate/renene

Estimating national and local low-voltage grid capacity for residential solar photovoltaic in Sweden, UK and Germany

Elias Hartvigsson [a, *], Mikael Odenberger [a], Peiyuan Chen [b], Emil Nyholm [a]

[a] Department of Space Earth and the Environment, Division of Energy Technology, Chalmers University of Technology, Sweden
[b] Department of Electric Engineering, Division of Electric Power Engineering, Chalmers University of Technology, Sweden

ARTICLE INFO

Article history:
Received 25 September 2020
Received in revised form
23 December 2020
Accepted 14 February 2021
Available online 3 March 2021

Keywords:
Residential solar PV
GIS
Sweden
Germany
United Kingdom
Hosting capacity

ABSTRACT

The electric grid's available capacity to accommodate solar photovoltaic on national scales is currently uncertain. This makes decisions about grid capacity expansion, which can be very costly for local grid operators, difficult to make. Yet, knowledge of national solar photovoltaic grid capacity is central in order to formulate realistic solar PV targets and strategies. We present a methodology based on publicly available data to estimate the grid's hosting capacity of residential solar photovoltaic at both the national and local scale. The model is applied to Sweden, Germany and the UK and shows that low-voltage grid capacity for residential solar photovoltaic is very large, 33 (+5/-7) GW (Sweden), 248 (+5/-24) GW (Germany) and 63 (+1/-14) GW UK, and similar to current total generation capacity. Based on our estimations, we find that with the capacity of the present grid Sweden can supply 24%, Germany 60% and UK 21% of their current annual net electricity consumption from residential solar photovoltaic. In addition, we find that the grid-supported individual solar PV system sizes increase as population density decreases. Finally, our work highlights the importance of implementing sizing incentives for customers when installing their solar PV systems.

1. Introduction

Solar photovoltaic (PV) is expected to play an important role in the transition towards a climate neutral energy system. Historically, solar PV has shown annual growth between 22 and 76% and has consistently exceeded growth expectations [1]. Germany, Italy and Greece have reached high penetration levels, and produced 7–8% of their annual electricity demand from solar PV in 2018 [2], and up to 40% during specific days [3]. Most of the current solar PV capacity is installed at residential or commercial properties. In Germany, 70% of the current solar PV capacity is installed in the low-voltage grids [4] and in Italy 98% of installations are found in the low-voltage grids [5]. Even though the costs for small-scale solar PV are higher than for utility-scale systems, smaller-scale solar PV is expected to account for about 40% of total PV capacity in 2050 [2,6]. During the last 18 years, the average individual solar PV system size for residential customers has increased from 2.4 kW to 6.4 kW [7], and will likely continue to grow as costs decrease.

Producing electricity locally has technical benefits, such as reducing losses and congestion in the grid [8]. However, electric grids are traditionally designed to transmit and distribute electricity from large centralized power plants to consumers, and can therefore be ill-prepared to handle distributed generation such as residential solar PV [9]. The emergence of distributed solar PV changes customers' traditional status as consumers, making them both producers and consumers instead, i.e. prosumers. This change in customer status influences the infrastructure required for operating power systems within stipulated regulations. The capacity for a power grid to handle solar PV within current regulations without requiring reinforcement is commonly known as hosting capacity [10]. The hosting capacity depends on multiple factors and assumptions and can vary significantly based on grid codes, electricity usage of customers and geographical distribution of the PV systems. For distributed solar PV, the two most common technical limiting factors for low voltage grids are upper voltage limits and thermal limits of components [11]. When the installed solar PV capacity surpasses a grid's local hosting capacity, grid reinforcement is required, which can require significant investment costs [12,13]. In Germany alone, costs for distribution grid, including low-

* Corresponding author.
E-mail addresses: Elias.hartvigsson@chalmers.se (E. Hartvigsson), Mikael.odenberger@chalmers.se (M. Odenberger), Peiyuan.chen@chalmers.se (P. Chen), Emil.nyholm@chalmers.se (E. Nyholm).

https://doi.org/10.1016/j.renene.2021.02.073
0960-1481/

voltage grids, reinforcements until 2030 due to distributed solar PV are estimated to be 28–42 billion euro [14].

For these reasons, significant research efforts have been made to identify the solar PV hosting capacity [15–18] and to develop competitive measures that can be used to increase the grid's hosting capacity [19–21]. Estimating and analysing hosting capacity traditionally requires access to grid data, which is often restricted, making most previous analysis limited to individual low-voltage grids covering a small neighbourhood. Results from such case studies in Sweden, the UK and Germany indicate that, depending on contextual factors and grid codes, residential customers installing solar PV systems sized between 1.3 and 5.5 kW may not require grid reinforcements, and thus, fall within the hosting capacity of the current grid. Previous studies have also shown that limitations to distributed solar PV first becomes apparent in low-voltage grids [22–24], which is supported by the focus on hosting capacity of low-voltage grids in previous research [13,15,17]. However, due to methodological and data access restrictions it is uncertain if these estimates are representative and there are currently no estimations of solar PV low-voltage hosting capacity on regional or national scales.

In light of the increased renewable electricity production many national and regional governments have set national targets for solar PV. Due to the lack of national and regional estimates on hosting capacity, current solar PV targets are politically set targets with little consideration for hosting capacity. National estimates and analysis of hosting capacity can contribute to estimating integration costs for renewables for different solar PV targets. Estimations of hosting capacity on national and regional scales are important in order to provide and assess residential solar PV targets, and can be used by regional and national governing bodies and regulators. Furthermore, knowledge about hosting capacity and its geographical distribution can improve resource estimations and limitations associated with residential solar PV in large scale energy system models. In this paper we present a methodology and an analysis of solar PV hosting capacity of residential customers on national and local scales for Sweden, Germany and the UK. The method is used to investigate national and local low-voltage solar PV hosting capacity in the respective countries. We avoid data-related restrictions by generating synthetic low-voltage residential networks based on national regulations and public high-resolution geographical data.

The paper is structured as follows. We start by providing a brief description of the method (a full description is found in Methods Details), followed by results which are divided into: model performance, national and local low-voltage residential solar PV hosting capacity and Limitations in residential solar PV hosting capacity. The paper ends with Discussion and conclusions.

2. Method

Here we present a brief description of the method, a full description of the method is found in the separate Method details. In order to make traditional estimations of solar PV low-voltage grid hosting capacity highly detailed data on grid components and layout is required. National data on grid components and topology are often distributed among tens to hundreds of operators. Furthermore, due to the importance of electric power systems as critical infrastructure, data often has security restrictions, further reducing accessibility to data. These data issues present a major barrier to estimating national levels of hosting capacity for solar PV. Yet, even with access to large datasets, the size and complexity of grids make traditional detailed power flow analysis infeasible.

We solve these issues by generating synthetic low-voltage grids using national standards and demand estimation methods using high-resolution geographical information system layers of demographics (see Table 2). Following most hosting capacity studies, we consider thermal limits based on capacity constraints of power system components and voltage variations at the Point of Common Connection (PCC). We consider the thermal limits to be fixed and determined by the respective component's ratings for nominal operating conditions. Voltage quality is determined based on voltage deviation and duration from its nominal value set by national and European regulations. Current European regulations state that a variation of $\pm$ 10% in low-voltage grids at the PCC is allowed [25], but many countries have stricter national limits [26–28]. In order to reduce this impact on our estimate, we use a stricter $\pm$ 5% voltage deviation in the low-voltage grid [29]. This effectively allows for a margin in voltage variation due to fluctuations in the medium voltage grid.

In order to generate the synthetic low-voltage grids we rely on three important assumptions. The assumptions highlight the trade-off between producing a large-scale estimate of solar PV hosting capacity and fine-scale accuracy. First, we limit our analysis to low-voltage grids. Only considering low-voltage grids significantly simplifies calculations and reduces complexity, but can reduce accuracy in areas where the supplying grid is weak (e.g. rural areas). Secondly, we limit our estimation to only include residential customers. Normally, models aimed at generating synthetic electric grids require input on customer location, which is kept by each network operator and normally not accessible to the general public. By excluding non-residential customers from our analysis, we can use high-resolution geographical information system data on population density and dwelling type to estimate customer location and type. Third, we use a previously established topology for low-voltage grids that focuses on modelling the longest feeder [30], e.g. a continuous stretch of cable or power line, from each transformer. Due to the large variation in feeder length in low-voltage transformers, focusing on the longest feeder simplifies comparisons between model output and data and makes the problem computational feasible. Focusing on the longest feeder likely causes a bias towards voltage violations in our results. We are interested in the technical hosting capacity, and therefore exclude economic limitations [31]. In addition, we exclude the impact from harmonics and flicker since the impact on hosting capacity is generally small, unless the grid is weak [32].

Hosting capacity is calculated in two modelling blocks consisting of four modelling steps (see Fig. 1). The first model block generates the synthetic low-voltage grids and includes the first three modelling steps (GIS load modelling, Transformer capacity allocation and Feeder length and feeder capacity estimation). The model block is independent, and the generated synthetic low-voltage grids can be used to assess grid impacts from other residential end-use technologies. The second model block focuses on grid operation, including operational regulations, and the fourth modelling step, Hosting capacity calculation. Fig. 1 shows a conceptual overview of the model.

Hosting capacity is calculated in cells (1×1 km^2). We assume that each household has a connection to a national low-voltage grid. Customers' grid connection is often regulated by national laws. In countries that allow for off-grid households, their total number is likely very small with negligible impact on the national

Table 1
Allocation of number of branches based on customers supplied by the medium to low-voltage transformer.

Number of Customers (NC)	NC > 100	100 > NC > 64	64 > NC > 36	36 > NC > 1	NC = 1
Branches	5	4	3	2	1

Table 2
Main model input and sources.

Input dataset	Load profiles (and annual electricity consumption for Sweden)	Low-voltage regulations	Dwelling distribution	Population density	Solar PV generation profiles
Sweden	Zimmerman et al. [38]	SEK [39]	Eurostat [40]	Statistics Sweden [41]	Norwood et al. [37]
Germany	VDI [34]	VDE [42]	Eurostat [40]	Eurostat [43]	Norwood et al. [37]
UK	Murray et al. [44]	IET [45]	Eurostat [40]	Eurostat [43]	Norwood et al. [37]

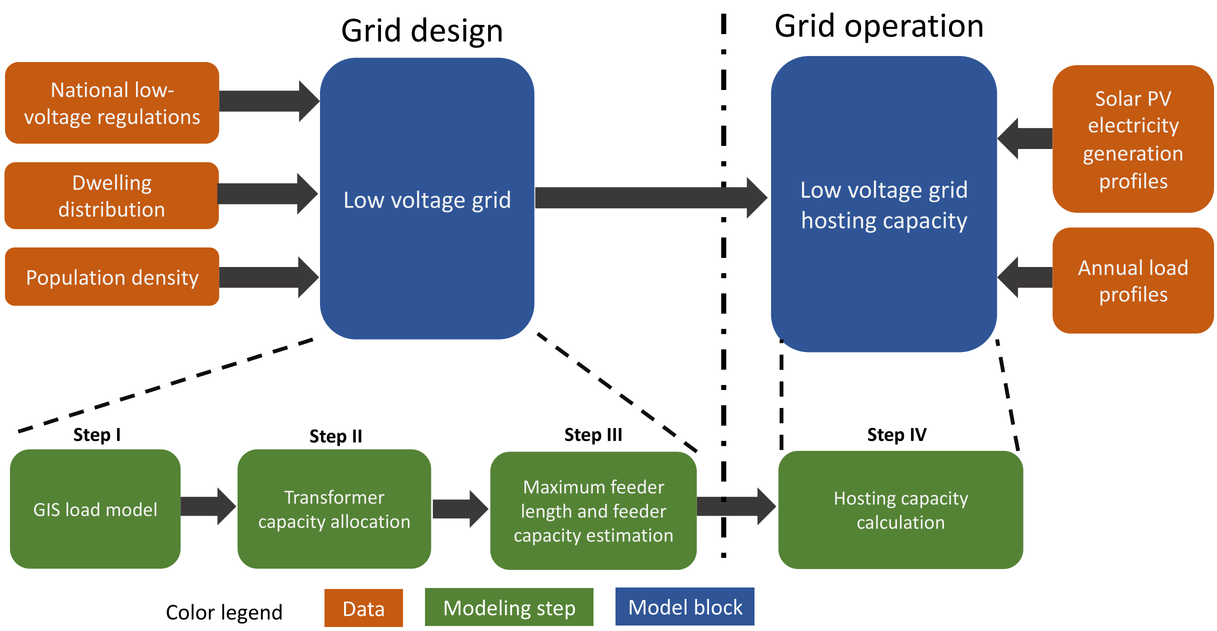

Fig. 1. Conceptual model framework, including the reference network model for the low-voltage grid and calculation of hosting capacity.

residential solar PV hosting capacity. For each cell, the GIS load model estimates peak power demand, P, using country-specific methods. We use Velander's formula for Sweden (Equation (1)), After Diversity Maximum Demand (ADMD) for the UK [33] (Equation (2)) and coincidence for Germany [34,35] (Equations (3) and (4)). The peak power demand is dependent on the number of customers, which is obtained from the population in each cell together with dwelling type.

$$P_{SWE} = NC \cdot E \cdot k_1 + k_2 \cdot \sqrt{NC \cdot E} \tag{1}$$

$$P_{UK} = NC \cdot ADMD \cdot Ft \cdot \left(1 + \frac{12}{ADMD \cdot NC}\right) \tag{2}$$

$$P_{DE} = NC \cdot g \cdot P_{peak} \tag{3}$$

$$g = g_\infty + \frac{1 - g_\infty}{NC} \tag{4}$$

where NC is the number of customers, E the annual electricity consumption, $ADMD$ the after diversity maximum demand, Ft a correction factor, g_∞ coincidence for an infinite number of customers and P_{peak} the peak power demand for a single customer.

Based on the calculated peak power demand, the number of transformers and their size is allocated using a cost-minimization strategy, where number and size of transformers are chosen to reduce total investment costs in a cell. The cost-minimization function is shown in Equation (5), with a capacity constraint shown in Equation (6).

$$C_i = NT_i \cdot C_{Tr,i} + l_{LV,i} \cdot C_{LV} + l_{MV,i} \cdot C_{MV} \quad i \in I \tag{5}$$

$$TR_{Cap,i} = \alpha \cdot P_D \quad i \in I \tag{6}$$

where I is a set of all possible transformer capacities, NT_i is number of transformers of type i, $C_{Tr,i}$ the cost of transformer size, $l_{LV,i}$ the total length of low-voltage lines, C_{LV} the cost of low-voltage lines per km, $l_{MV,i}$ the marginal length of medium-voltage lines, C_{MV} the cost of medium-voltage lines per km, $TR_{Cap,i}$ is the capacity of transformer i, and α transformer margin. The transformer margin allows for a future growth in demand.

When the number of transformers has been calculated, the area supplied by each transformer A_{Tr} is obtained by dividing the cell area by the number of transformers. Assuming a uniform distribution of customers in the area supplied by each transformer, and with horizontal and vertical connection lines, the maximum feeder length is calculated according to Ref. [30], which becomes:

$$l_{max} = \sqrt{A_{Tr}}\ \frac{\left(\sqrt{NC_{Tr}} - 1\right)}{\sqrt{NC_{Tr}}} \cdot \gamma \tag{7}$$

where NC_{Tr} is the number of customers supplied by each transformer and γ an adjustment factor. Feeders are often not drawn in straight lines, but follow local topology such as roads. The adjustment factor aims to compensate for this discrepancy [30]. Normally, low-voltage feeders exhibit varying levels of branching. Branching is the sectioning of a feeder to multiple feeders. The number of branches for each feeder is set depending on the number of customers according to Table 1. The highest number of branches allowed is five.

Hosting capacity calculations are sensitive to how solar PV systems are allocated in a low-voltage grid. Methods for allocation can be divided into stochastic and deterministic [36]. Stochastic methods randomly assign a location and size for a solar PV system given certain restrictions. Stochastic allocation methods result in a solution space that contains a wide range of solar PV deployment scenarios but require more computing power. Due to the large geographical scope, and to make the problem computationally feasible we rely on a deterministic allocation method, where all solar PV systems are equally sized. Using the maximum feeder calculated in Equation (7) and the transformer capacity from Equation (5), the solar PV system sizes are simultaneously increased for all customers in steps of 0.5 kW until either the upper voltage level is reached (Equation (8)), or the thermal limit of either the feeder or transformer is reached (Equations (8) and (9)).

$$U^{Upper}_{p.u} \leq 1.05\ p.u \tag{8}$$

$$max(|P_{D,net}(t)|) \leq TR_{cap} \tag{9}$$

$$max(|P_{D,net,j}(t)|) \leq Feeder_{Cap,j} \tag{10}$$

where $|P_{D,net}(t)|$ is the net power demand for each household, $Feeder_{Cap,j}$ is feeder thermal capacity at location j and TR_{cap} is transformer thermal capacity. The net power demand is obtained using national high-resolution (10 min) annual residential load profiles and PV generation profiles from Ref. [37], which is based on the MERRA-2 dataset for the year 2012. The annual solar production from a household's solar PV system becomes

$$PV_{Annual} = \sum_{t=1}^{52560} PV_{HH} \cdot PV(t) \tag{11}$$

where PV_{HH} is the per-household solar PV hosting capacity in kW, $PV(t)$ the solar production profile and 52560 refers to the number of 10 min periods in a year. All data sources used in the model are public and can be found for most countries (see Table 1 for datasets and sources and Table A2 – A5 in the Appendix for model parameters). The limiting factor for expanding the method is either acquiring annual load profiles with a sufficient temporal resolution (10 min or higher based on European voltage regulations [25]), or identifying national methods for estimating residential demand.

3. Results

3.1. Model performance and sensitivity analysis

The lack of access to grid data and case studies makes validation difficult in reference network models. We therefore use a range of datasets to build confidence that our model produces realistic results. The model's performance in predicting transformer density and maximum feeder length is cross-validated using grid data from 373 Medium-to-Low voltage substations from eight areas, supplying about 215 000 customers in Sweden (see Fig. 2A and Fig. 3). Due to difficulties assigning a transformer's supply area to a specific cell, transformer density in Fig. 2A is shown for each area. On Average the model underestimates mean transformer density with 40%, with a larger error in cities (Fig. 2A). The underestimation of mean transformer density is expected as we exclude non-residential customers, who represent about two thirds of electricity consumption in Sweden. The model's ability to predict maximum feeder length varies significantly among different areas and is more precise for feeder lengths between 300 m and 800 m. Between half and two thirds of feeders in Sweden and the UK are between 300 and 800 m [46]. Fig. 3I shows the independently sorted maximum feeder lengths for all areas, e.g. the figure shows a comparison between the distribution of feeder lengths between the model and the compared areas, and not comparisons between specific areas. Compared to the performance in single instances (Fig. 3A–H), this highlights our model's improved accuracy in large diverse datasets compared to its accuracy in individual cells. This impacts the high-resolution accuracy on the model but is less consequential for regional and national estimates.

Finally, we compare the model's ability to predict grid-supported solar PV system sizes with eight case studies from Sweden, Germany and the United Kingdom (Fig. 2B, additional details in Table A1). A direct comparison between case studies and model output is difficult due to methodological differences as well as differences in considered factors and demographic areas. This limited the number of case studies that are suitable for comparisons to eight. Some of the case studies include multiple low-voltage grids, which are shown as separate data points in Fig. 2B. We adapt our model to each study's contextual factors, e.g. thermal and voltage limits and demographic area. For Sweden and the UK, demographic data for each case study is estimated based on available information (if it is a rural, urban or city area, number of customer supplied by each transformer and area coverage of each transformer) while for the German case studies, the exact locations (and therefore demographics) are known. On average, our model underestimates the average potential solar PV system size by10%, but with large errors in individual cases. The largest errors in predicted mean solar PV system size are found in case studies that explicitly investigate old low-voltage grids or target areas with a large share of non-residential electricity demand.

We conduct a sensitivity analysis for two parameters: transformer sizing (α, Equation (6)), adjustment factor (γ, Equation (7)) and one input: electricity consumption. Due to long computational times, variation in parameter values is limited. Transformer margin (α) is varied between 1.2 and 2.4 in steps of 0.3, adjustment factor (γ) is varied from 1 and 1.3 in steps of 0.1. Three different electricity usage load profiles are used: no electricity consumption, medium electricity consumption and high electricity consumption. Medium and high electricity consumption is estimated from peak demand

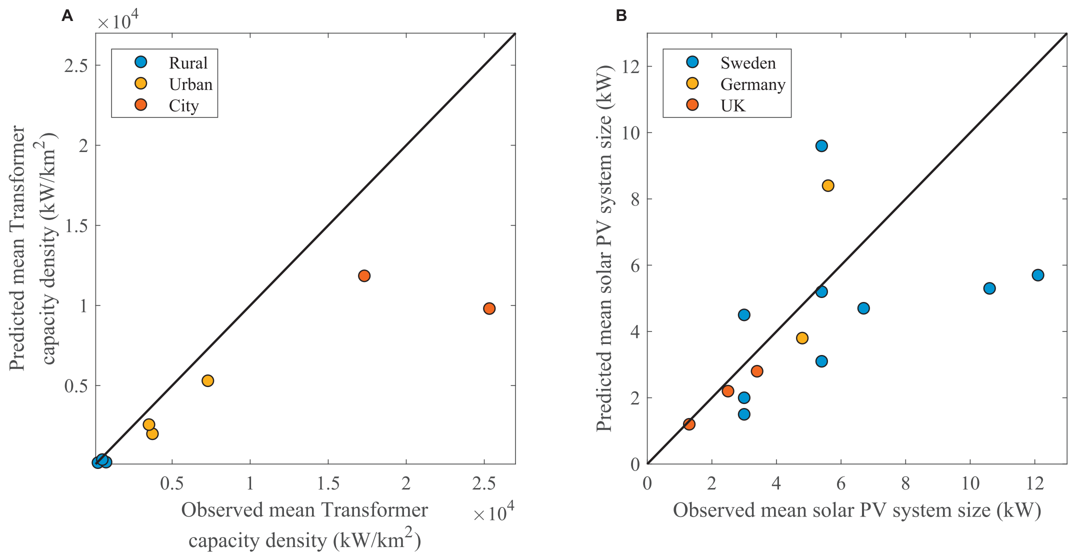

Fig. 2. Comparison plots for transformer capacity density and solar PV system size. Diagonal line indicates 1:1 line (perfect correspondence). **A**, Predicted mean transformer density for the eight geographical areas in Sweden shown in Fig. 2. On average the model underestimates transformer density with 40%. **B,** Predicted grid supported solar PV system size per household compared to observed solar PV system sizes in Sweden, Germany and the UK. On average, the model underestimates mean solar PV system size 10%. Details on the compared case studies are found in the Appendix.

and annual electricity consumption based on the available electricity load profiles for each country. No electricity consumption assumes that households consume no electricity, which results in no production locally offset by consumption. The impact on national hosting capacity is normalized and shown in Fig. 4. Transformer margin has the largest impact in all three countries. The impact on Electricity usage has large variation by country. The variation is likely due to the source of electricity usage data. In Germany, with the lowest variation, we used a single electricity usage load profile from the German standardization organisation, VDI [34]. In Sweden and the UK, we used different measured load profiles from large databases [38,44]. The low impact stemming from variations in gamma is explained by longer line length being compensated for in the design process (i.e. capacity is increased to comply with standards and regulations on voltage drop and tripping times).

3.2. National and local low-voltage residential solar PV hosting capacity

Our model provides a national spatial map of low-voltage hosting capacity in Sweden, Germany and the United Kingdom (Fig. 5 and Fig. 6) using European local administrative units [47]. Local administrative units are the highest resolution geographical level at which the European statistical office provides data. Furthermore, the demographic diversity in local administrative units increases the model's accuracy as shown in Fig. 3. Based on this map, we aggregate hosting capacity for all low-voltage grids in each country and estimate the national low-voltage hosting capacity, including sensitivity runs in parentheses, for residential solar PV to be 33 (+5/-7) GW (Sweden), 248 (+5/-24) GW (Germany) and 63 (+1/-14) GW (United Kingdom). The low-voltage hosting capacity for residential solar PV in each country is similar to the current total installed generation capacity in Sweden (41 GW) and Germany (211 GW) and slightly lower in the United Kingdom (105 GW).

At the local administrative unit level, the hosting capacity density (MW/km^2) shows a high level of heterogeneity (Fig. 5). Sweden has significantly lower hosting capacity density than Germany and the United Kingdom. Differences in hosting capacity density are mainly explained by differences in demographics. Hosting capacity density correlates with population density (Fig. 7B). Areas with large hosting capacity density are therefore focused in densely populated areas. The United Kingdom and Germany are more densely populated than Sweden and therefore have an overall higher hosting capacity density. Areas with higher population density have higher demand density, as low-voltage grids are designed to supply load within a geographic area, higher load density requires larger grid capacity. Higher grid capacity has a positive impact on hosting capacity, leading to high hosting capacity density in areas with high population density.

On a national level, the average solar PV system size per household that the low-voltage grid supports is 7.2 (+1.1/-1.5) kW (Sweden), 6.2 (+0.1/-0.6) kW (Germany) and 2.3 (+0/-0.5) kW (United Kingdom). In terms of the size of individual solar PV systems that the grid can support, the relationship with population density is to a large extent reversed, with the grid supporting larger individual solar PV systems in sparsely populated areas than in densely populated areas (Figs. 6 and 7A). This may seem surprising but is explained by the non-linearity of power estimation methods and issues of matching power system components to power demand. When estimating the peak load in an area, grid operators take into account the likelihood that all individual customers' peak load will occur simultaneously. This likelihood decreases with an increase in the number of customers. The per-customer power demand that grid operators design their system for therefore decreases with the number of customers [48]. This effect is reinforced by a larger mismatch between peak load and power system component's capacity in areas with few customers. The mismatch is due to the discrete steps that power system components, such as transformers and cables, are available in, and requirements on voltage drop and earth impedances.

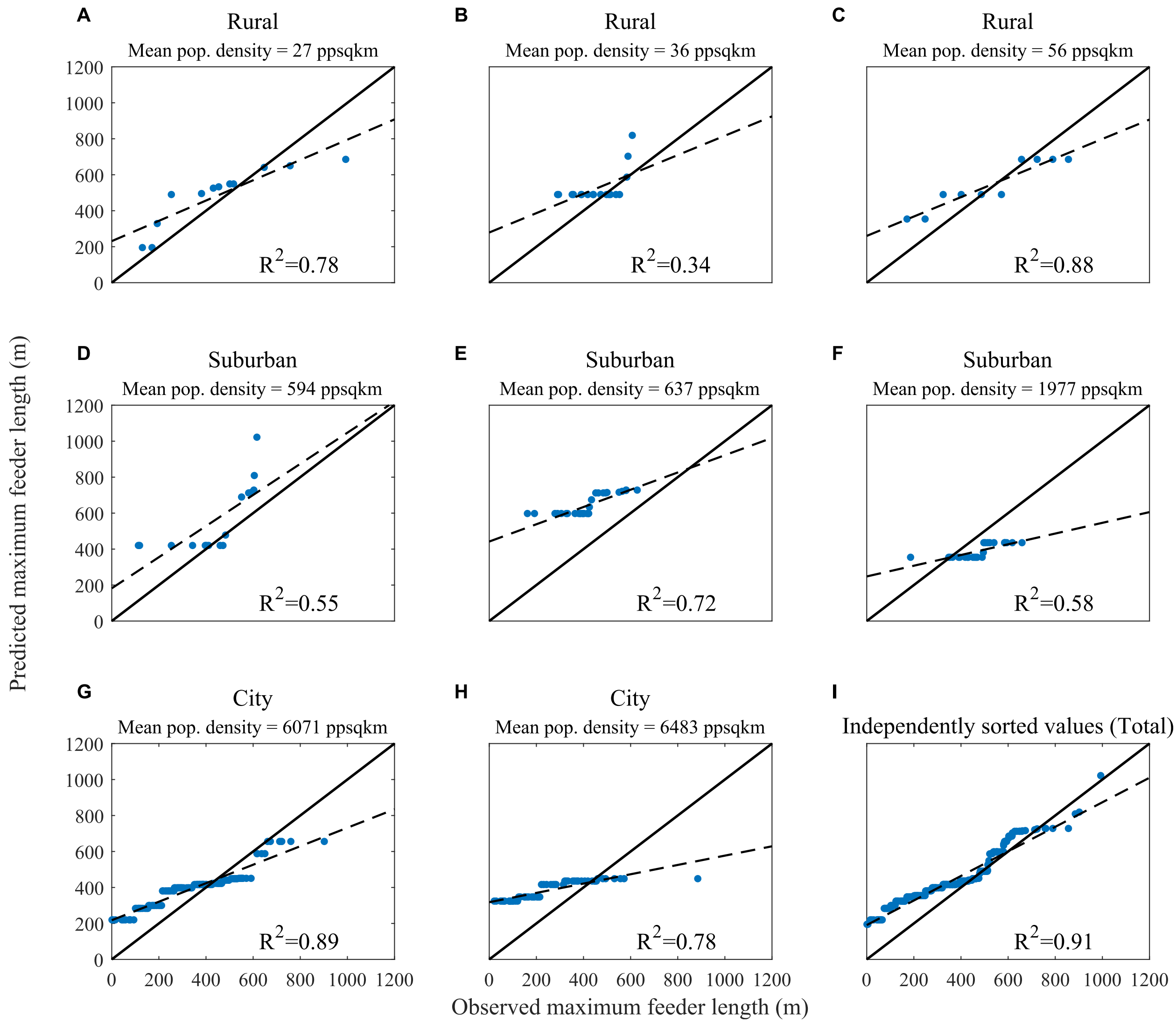

Fig. 3. Model performance plots for maximum feeder length. Data on maximum feeder length per Medium-to-Low voltage transformer (n = 373) in Sweden. Blue dots show individual feeders and solid lines indicate 1:1 lines (perfect correspondence). Dashed lines indicate fitted relationship with R^2 values in the bottom of each figure. The *R*2value indicates theoretical discrepancy between predicted and observed values while the difference between the dashed and solid lines highlights model offset. Unit for population density (ppsqkm) is population per square km. **A-H**, shows validation plots for eight geographical areas representing a wide range of population densities. In 33% of the cases, data has been interpolated due to differences in number of Medium-to-Low voltage transformers. Differences in the number of Medium-to-Low voltage transformers is mainly due to our exclusion of non-residential electricity demand and local topology, such as roads, lakes and rivers. **I**, shows independently sorted values for the whole dataset and not predicted compared to observed values for specific geographic locations.

The heterogeneity between countries in grid capacity for individual solar PV system sizes is explained by differences in current and historical use of electricity and demographics. Sweden has a history of using electricity for residential heating while Germany and the United Kingdom have mostly relied on natural gas [49]. The high coincidence and power demand of electric heating have required Swedish low-voltage grids to be built for a higher per-customer peak demand than the corresponding low-voltage grids in Germany and United Kingdom, resulting in larger hosting capacity for solar PV. This can be seen in Fig. 7A, where the average per-household system size that the low-voltage grid can support for specific population densities is higher for Sweden than Germany, and lowest for the UK, for population densities larger than 10 people per square km.

In addition, differences in grid-supported solar PV system sizes are reinforced by demographics. Areas with one or only a few customers per transformer tend to have short maximum feeder lengths, around 100–300 m, supplying one or two customers, and large transformer capacity per customer. In these cases, the low-voltage grid supports very large individual solar PV systems, ranging from 20 to 45 kW. Depending on demographics in each country, the contribution from these cases on national and local hosting capacity varies. Sweden has a more rural population than Germany or the UK. In Sweden, 2.7% of the population lives in areas with $\leq$ 10 people per square km, while in Germany the share is 0.27% and in the United Kingdom 0.21%.

Using annual solar insolation from the MERRA-2 dataset for 2012 and the hosting capacity, we generate an annual solar PV electricity production (Fig. 8). The implications of the larger average grid-supported solar PV system size in Sweden and Germany become apparent when examining average annual electricity production per customer. Sweden, with the lowest annual solar insolation of the three countries shows the largest annual electricity production per customer. On a per-customer basis, Sweden's grid

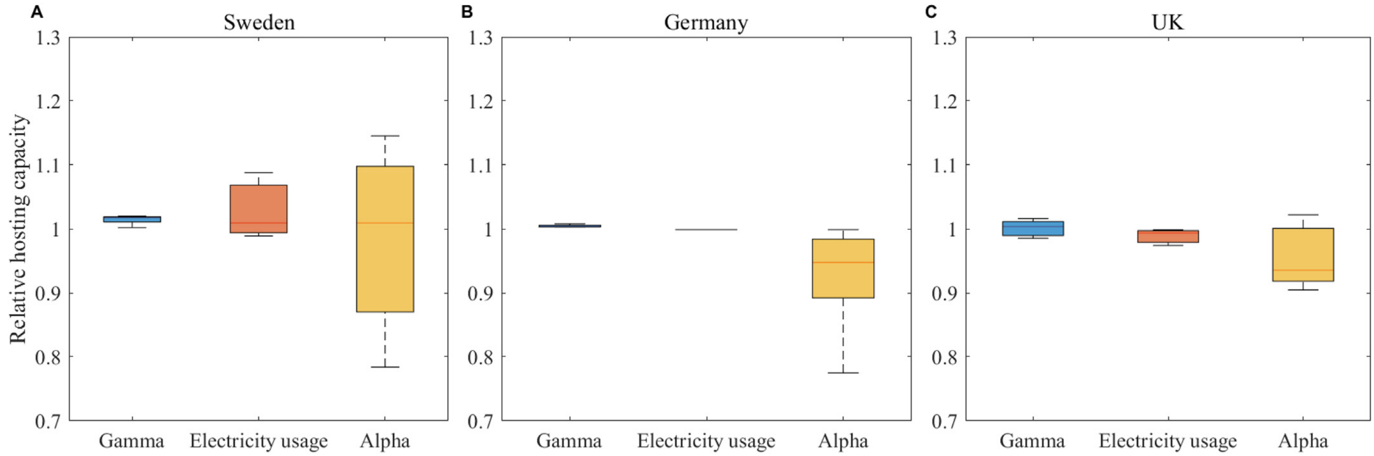

Fig. 4. Sensitivity analysis for two model parameters (Gamma and Alpha) and one dataset (Electricity usage). Simulation runs shown for Sweden (**A**), Germany (**B**) and UK (**C**).

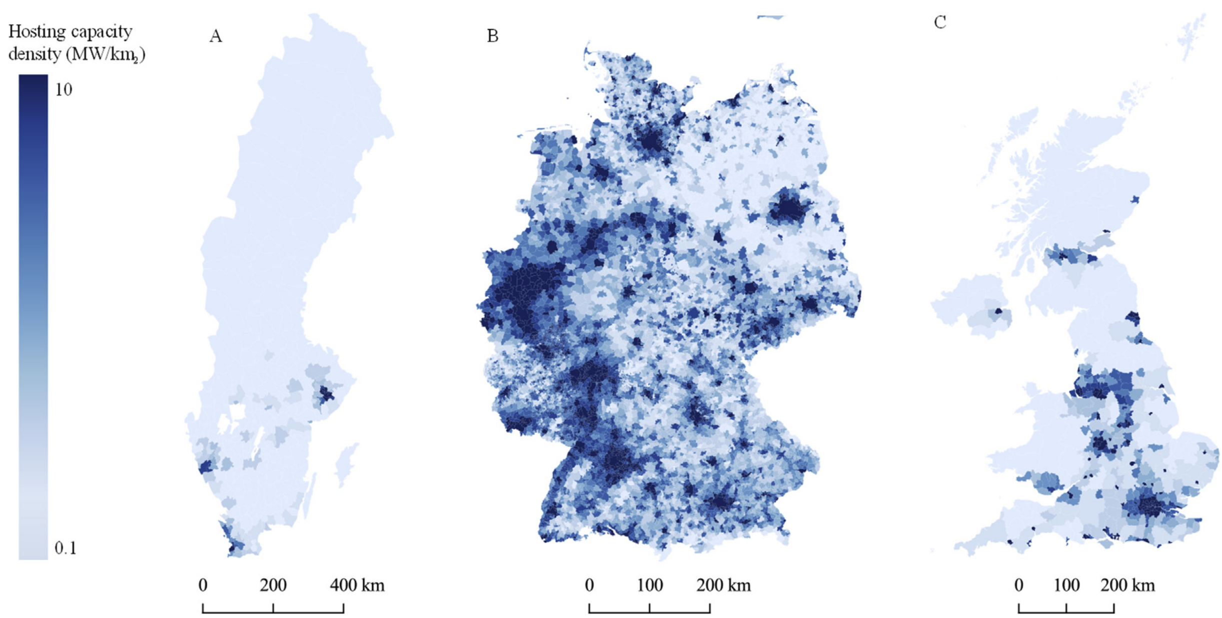

Fig. 5. Hosting capacity density map (MW/km^2) aggregated to local administrative units. Darker colours represent larger hosting capacity density. The colour scale is logarithmic to account for the large variation in hosting capacity density. Results shown for Sweden (**A**), Germany (**B**), and the United Kingdom (**C**). Note due to rounding error in the GIS aggregation, summation of hosting capacity density might not correspond to national hosting capacity.

can support larger electricity production from residential solar PV than Germany, despite lower annual solar insolation. The UK, which has comparably lower annual solar insolation and smaller average residential solar PV systems, shows a significantly lower average annual electricity production per customer (2–3 times lower than Sweden). Accordingly, the national hosting capacity expressed as annual electricity production from residential solar PV, is 34 (+5/-6) TWh (Sweden), 307 (+6/-30) TWh (Germany) and 69 (+1/-15) TWh (UK) of electricity respectively, which corresponds to an annual share of electricity consumption of about 24% (Sweden), 60% (Germany) and 21% (UK). The larger share of total electricity consumption in Germany compared to Sweden is due to a significantly larger electricity consumption per capita in Sweden.

3.3. Limitations in residential solar PV hosting capacity

Our model also provides insights into how residential solar PV hosting capacity is limited in each of the three countries. The distribution of limiting factors has a direct impact on establishing national strategies for managing hosting capacity. Our results show that in Germany the limiting factors are primarily voltage increase (57%) and lack of transformer capacity (38%) (Fig. 9). This is consistent with a recent survey of implemented grid reinforcements due to solar PV among German distribution system operators [13]. The share between voltage increase (42%) and lack of transformer capacity (40%) is similar in Sweden, while in the United Kingdom the primary limiting factor is voltage increase (85%). The large share of solar PV systems that are limited by voltage variations in all three countries suggests that national strategies focusing on voltage control, such as reactive power feed-in by the inverter, changing the tap-ratio of transformers or voltage control of entire medium-voltage feeders or transformers, would be efficient in increasing national low-voltage hosting capacity, notably in Germany and the United Kingdom. The larger share of capacity-limited systems (60%), notably in Sweden, suggests that measures focused at increasing the current carrying capacity of

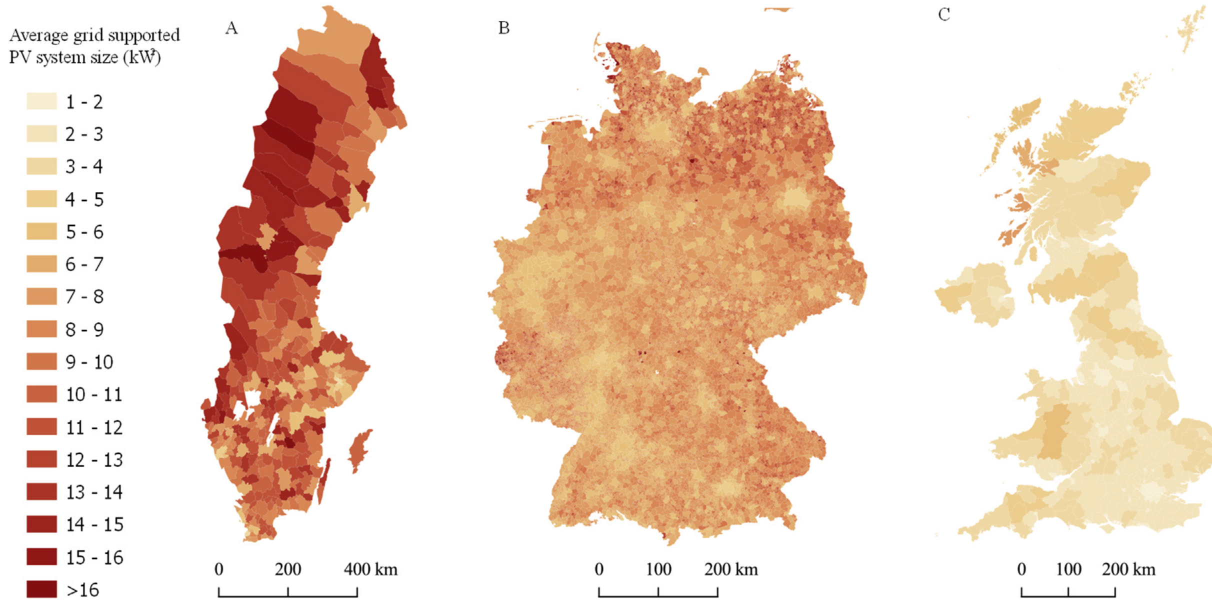

Fig. 6. Mean grid supported individual residential solar PV systems aggregated to Local Administrative Units. Darker colours represent larger average grid supported solar PV systems. Results for Sweden (**A**), Germany (**B**) and UK (**C**). Grid support for average solar PV system sizes above 10 kW are generally found in areas with very low population densities (<30 people/km^2).

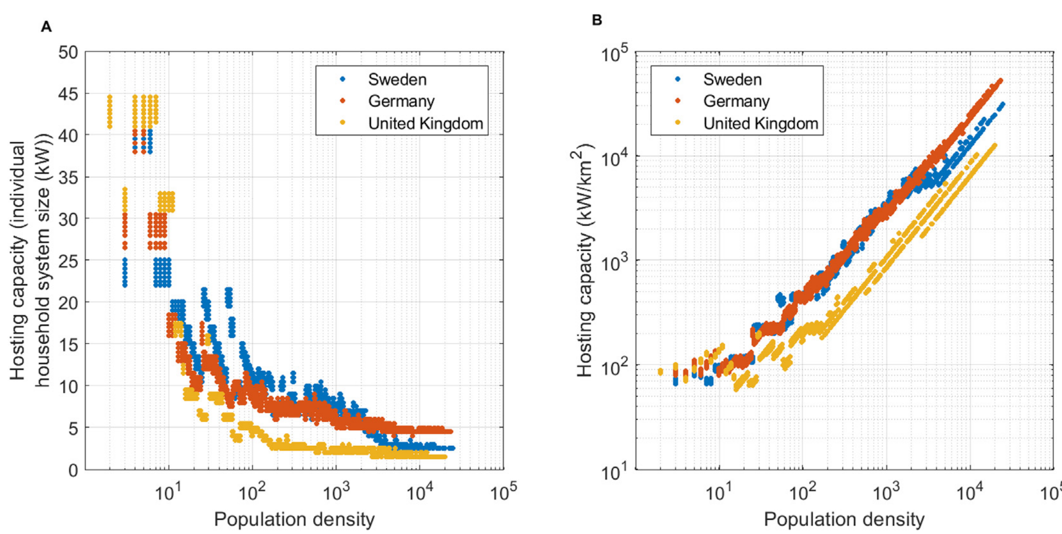

Fig. 7. Data plots of hosting capacity as a function of population density. Results shown for individual household solar PV system size (**A**) and hosting capacity density (**B**). Log or semilog plots used due to large variation in data.

components would be efficient strategies for increasing national low-voltage hosting capacity. Measures for increasing the current carrying capacity include solar PV curtailment, dynamic transformer or cable loading, transformer or cable upgrade or installation of large-scale battery systems.

4. Discussion and conclusions

There are many aspects that impact hosting capacity estimates. We conducted a sensitivity analysis of two parameters (alpha and gamma) and different electricity load profiles, which capture variation related to model parameterization. In addition, our model relies on a number of assumptions and simplifications. One of our primary assumptions is to limit the analysis to low-voltage grids. Omitting the supply grid (MV-grid) from our modelling risks underestimating the voltage variations and ignoring lack of thermal capacity in the upstream medium voltage feeders and/or transformers. This could lead to an overestimation of the PV hosting capacity. The impact from voltage variation in the medium-voltage grid will likely be due to long medium-voltage feeders, more commonly found in rural areas, or due to increase in the supplying voltage due to a large share of solar PV installations in the supplied area. Yet, our choice to limit the analysis to the longest feeder in the low-voltage grid is likely to cause over estimation of voltage violations. While they are unlikely to cancel each other out, these two assumptions likely have a balancing impact on the results. Furthermore, our choice of limiting voltage increase to 5% in the low-voltage grid leaves a margin of voltage variation in the supplying medium voltage grid given current EU regulations on voltage increase. The 5% voltage limit should reduce overall errors

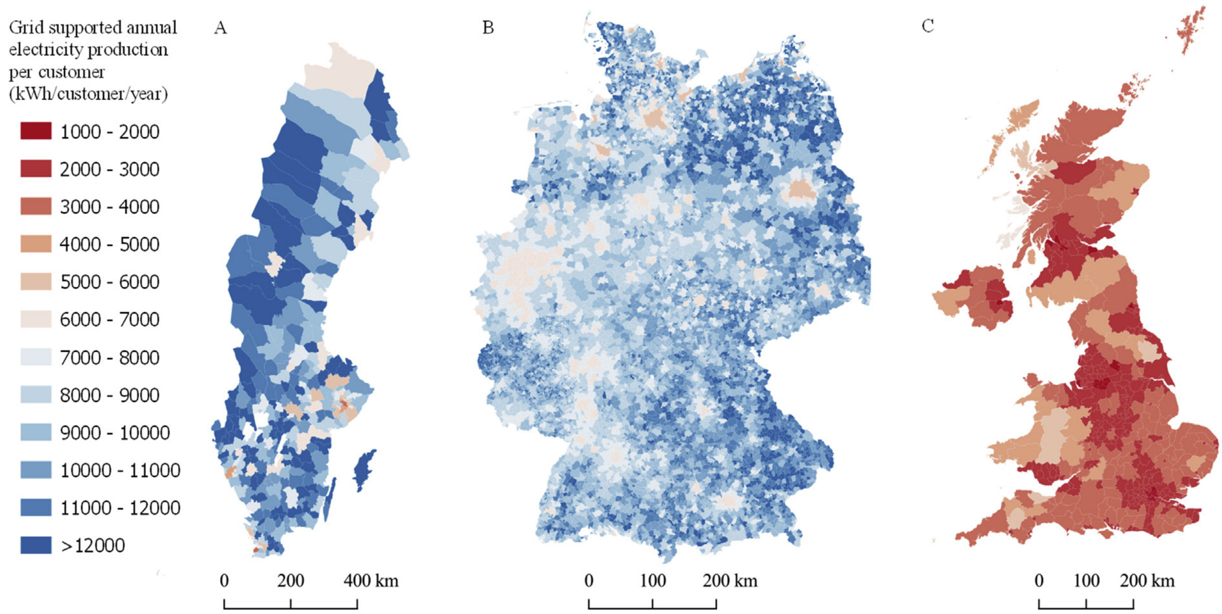

Fig. 8. Grid supported annual per customer electricity production in kWh aggregated to local administrative units. Blue represents larger and red smaller annual PV electricity production. Results shown for Sweden (**A**), Germany (**B**) and UK (**C**). Note due to rounding errors in the GIS aggregation, summation of per customer annual electricity might not correspond to national electricity production.

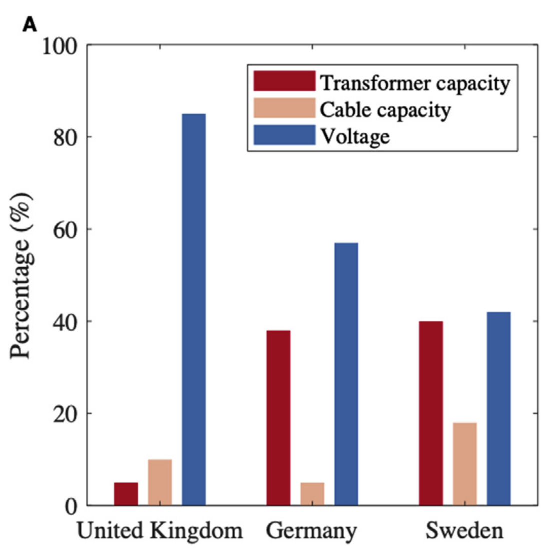

Fig. 9. Limitations in residential solar PV deployment. Limiting factor for residential solar PV for United Kingdom, Germany and Sweden.

due to voltage increase in the medium voltage grid, and provide a lower estimate of low-voltage hosting capacity.

Areas with only a few customers per transformer, where we found the low-voltage grids to be able to support individual system sizes between 20 and 45 kW, might be limited earlier due to voltage variation in the medium-voltage grid. The contribution of these types of areas to national hosting capacity estimates varies with each country, but never exceeds 13%. Additional research on where grid limitations occur and the impact of the medium-voltage grid in such areas would be useful. The availability of thermal capacity in medium voltage feeders and in high-to-medium voltage transformers could also provide limitations in areas with little consumption to match the solar PV output.

A key determinant for hosting capacity is the designed load. We have relied on commonly used methods for estimating residential loads, which are specific for each country. These methods have often been developed from historical experience on residential demand. With a large change in residential electricity consumption and production arising from solar PV, EV charging and electricity based heating, many network operators have likely adapted their demand estimation accordingly. Recently designed low-voltage grids might therefore have a different hosting capacity than what is estimated using our method. Low-voltage grids designed 40–50 years ago will likewise have been built using different demand estimation methods. Furthermore, including non-residential loads would improve the model's performance, specifically in areas with a large non-residential demand.

Customer locations within each cell were assumed to be uniform. This causes the model to underestimate feeder length in some instances, and overestimate feeder length in other instances, see Fig. 3. If customer location could be modelled more accurately, for example using additional datasets on building footprint, the model performance would improve, especially its high-resolution performance. Such data is currently available, but only for limited areas, from OpenStreetMap. Even though the presented method has been used to assess residential solar PV hosting capacity, the generated low-voltage grids can be used to analyse issues arising from adoption of other residential end-use technologies, e.g. electric vehicles or electric heating.

Our results show an attempt to estimate low-voltage hosting capacity for residential solar PV on national and local scales. While there is large grid capacity for residential solar PV this is not utilized efficiently at present. Germany, which has about 46 GW of installed solar PV, far below their estimated residential hosting capacity of 248 (+5/-24) GW, has already required and plans grid reinforcements in the order of tens of billions euros [13]. The discrepancy between our reported low-voltage hosting capacity and the already need for grid reinforcements in Germany is mainly explained by how solar PV system sizes are allocated in our model. For a given low-voltage transformer we assume that all households install an equally large solar PV system. This method likely causes an overestimation of hosting capacity compared to an approach where sizes vary significantly. In reality, there are large variations among households, some households install very large solar PV systems. Specifically, if a household far away from the transformer installs a large system, it is possible to reach hosting capacity at much lower solar PV capacities than the ones reported by our model. A stochastic sizing and allocation method was not feasible due to computational resources required by the model.

There is therefore a risk that if a household's incentives for installing solar PV systems do not account for grid limitations this can lead to an inefficiently used hosting capacity and need for large-scale grid reinforcements. Hence, there are large financial gains to be made in avoiding grid reinforcements if solar PV systems are allocated and sized appropriately. Even though current regulations on grid reinforcements due to installed solar PV vary between countries, reinforcement costs are ultimately transferred to customers. The average solar PV system size that the grid can support in each country can serve as an indicator for how likely each country is to require grid reinforcements. Without any incentives for households to consider grid limitations, the lower grid supported residential solar PV systems in the United Kingdom suggests that they would require grid reinforcements at an earlier stage than Sweden or Germany.

CRediT authorship contribution statement

Elias Hartvigsson: Conceptualization, Methodology, Software, Writing – original draft. **Mikael Odenberger:** Conceptualization, Writing – review & editing, Funding acquisition, Supervision. **Peiyuan Chen:** Conceptualization, Writing – review & editing, Supervision. **Emil Nyholm:** Methodology, Software, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

The authors would like to thank Professor Per Norberg for discussions on grid design. E.H thanks the Area of Advance Energy at Chalmers for providing financial support.

Appendix

Table A1
Data used for comparison plots in Fig. 2.

Source	Type of area	Country	Observed solar PV system size	Predicted solar PV system size	Error
[15]	Rural	Sweden	3 kW	1.5 kW	−50%
[15]	Urban (electric heating)	Sweden	3 kW	2 kW	−33%
[15]	Urban (district heating)	Sweden	3 kW	4.5 kW	+50%
[50]	Rural	Sweden	5.4 kW	3.1 kW	−44%
[50]	Urban (modern)	Sweden	5.4 kW	5.2 kW	−4%
[50]	Urban (old)	Sweden	5.4 kW	9.6 kW	+78%
[51]	Rural, Urban and town	Sweden	6.7 kW	4.7 kW	−30%
[51]	Urban	Sweden	10.6 kW	5.3 kW	−50%
[51]	Town	Sweden	12.1 kW	5.7 kW	−53%
[52]	Urban	UK	2.5 kW[1]	2.2 kW	−12%
[53]	Urban	UK	1.3 kW	1.2 kW	−8%
[54]	Urban	Germany	3.4 kW	2.8 kW	−18%
[55]	Urban	Germany	4.8 kW	3.8 kW	−21%
[56]	Urban	Germany	5.6 kW	8.4 kW	+50%
Average	–	–	4.5 kW	4.0 kW	−10%

[1] The study actually reports a solar PV system size of 4 kW. However, this system size is divided over rooftops with various inclination and orientations, resulting in a maximum simultaneous production of approximately 2.5 kW per customer for the given voltage variation. Since our model assumes a constant maximum production capacity using a southern orientation of the PV systems without taking the rooftop area or its angle into consideration, 2.5 kW per customer better matches our assumptions.

Table A2
General model parameters, values and sources.

Parameter	α	γ_{City}	γ_{urban}	γ_{rural}	pf	$Fuse_{Apt}$	$Fuse_{House}$
Value	1.8	1.2	1.1	1	0.95	10A	20A
Source	[57]	[30]	[30]	[30]	Assumed	Assumed	Assumed

Table A4
UK specific model parameters, values and sources for household size and ADMD coefficients.

Parameter	Household size	Ft	$ADMD_{Apt}$	$ADMD_{House}$
Value	2.35	0.7	1.5	2.1
Source	[60]	[33]	[33]	[33]

Table A3
Swedish specific model parameters, values and sources for Household size and the Velander equation. Household size has been adjusted upwards in order for the results to be consistent with the total number of households in Sweden.

Parameter	$Household\ size_{Apt}$	$Household\ size_{House}$	$k_{1,Apt}$	$k_{2,Apt}$	$k_{1,House}$	$k_{2,House}$
Value	2	2.7	0.000264	0.014	0.0003	0.0375
Source	[58]	[58]	[59]	[59]	[59]	[59]

Table A5
German specific model parameters and parameter values for household size and coincidence for infinity number of customers.

Parameter	Household size	g_∞
Value	2	0.3
Source	[61]	[35]

References

[1] F. Creutzig, P. Agoston, J.C. Goldschmidt, G. Luderer, G. Nemet, R.C. Pietzcker, The underestimated potential of solar energy to mitigate climate change, Nat. Energy 2 (2017) 17140, https://doi.org/10.1038/nenergy.2017.140.
[2] REN21, Renewables 2019 - Global Status Report, 2019.
[3] Fraunhofer Institute, Net Public Electricity Generation in Germany in 2018, 2019. https://www.ise.fraunhofer.de/content/dam/ise/en/documents/News/Stromerzeugung_2018_2_en.pdf. (Accessed 25 September 2020).
[4] J. von Appen, M. Braun, T. Stetz, K. Diwold, D. Geibel, Time in the sun: the challenge of high PV penetration in the German electric grid, IEEE Power Energy Mag. 11 (2013) 55–64, https://doi.org/10.1109/MPE.2012.2234407.
[5] Gestore Servizi Energetici, Rapporto Statistico Sul Solare Fotovoltaico, 2019. https://www.gse.it/documenti_site/Documenti GSE/Rapporti statistici/Solare Fotovoltaico - Rapporto Statistico 2018.pdf. (Accessed 25 September 2020).
[6] U.S Energy Information Administration, Annual Energy Outlook, Washington DC, 2019.
[7] G. Barbose, N. Darghouth, Tracking the Sun: Pricing and Design Trends for Distributed Photovoltaic Systems in the United States, 2019, p. 52. https://emp.lbl.gov/publications/tracking-sun-pricing-and-design. (Accessed 25 September 2020).
[8] V.H.M. Quezada, J.R. Abbad, T.G.S. Roman, Assessment of energy distribution losses for increasing penetration of distributed generation, IEEE Trans. Power Syst. 21 (2006) 533–540, https://doi.org/10.1109/TPWRS.2006.873115.
[9] R.A. Walling, R. Saint, R.C. Dugan, J. Burke, L.A. Kojovic, Summary of distributed resources impact on power delivery systems, IEEE Trans. Power Deliv. 23 (2008) 1636–1644, https://doi.org/10.1109/TPWRD.2007.909115.
[10] H.M. Bollen, K.S. Rönnberg, Hosting capacity of the power grid for renewable electricity production and new large consumption equipment, Energies 10 (2017), https://doi.org/10.3390/en10091325.
[11] J.A.P. Lopes, N. Hatziargyriou, J. Mutale, P. Djapic, N. Jenkins, Integrating distributed generation into electric power systems: a review of drivers, challenges and opportunities, Elec. Power Syst. Res. 77 (2007) 1189–1203, https://doi.org/10.1016/J.EPSR.2006.08.016.
[12] K.A.W. Horowitz, B. Palmintier, B. Mather, P. Denholm, Distribution system costs associated with the deployment of photovoltaic systems, Renew. Sustain. Energy Rev. 90 (2018) 420–433, https://doi.org/10.1016/J.RSER.2018.03.080.
[13] B. Bayer, P. Matschoss, H. Thomas, A. Marian, The German experience with integrating photovoltaic systems into the low-voltage grids, Renew. Energy 119 (2018) 129–141, https://doi.org/10.1016/J.RENENE.2017.11.045.
[14] IEA-PVPS, High Penetration of PV in Local Distribution Grids, Paris, France, 2014.
[15] J. Widén, E. Wäckelgård, J. Paatero, P. Lund, Impacts of distributed photovoltaics on network voltages: stochastic simulations of three Swedish low-voltage distribution grids, Elec. Power Syst. Res. 80 (2010) 1562–1571, https://doi.org/10.1016/J.EPSR.2010.07.007.
[16] R. Tonkoski, D. Turcotte, T.H.M. El-Fouly, Impact of high PV penetration on voltage profiles in residential neighborhoods, IEEE Trans. Sustain. Energy 3 (2012) 518–527, https://doi.org/10.1109/TSTE.2012.2191425.
[17] J.D. Watson, N.R. Watson, D. Santos-Martin, A.R. Wood, S. Lemon, A.J.V. Miller, Impact of solar photovoltaics on the low-voltage distribution network in New Zealand, IET Generation, Transm. Distrib. 10 (2016) 1–9.
[18] M. Thomson, D.G. Infield, Impact of widespread photovoltaics generation on distribution systems, IET Renew. Power Gener. 1 (2007) 33–40, https://doi.org/10.1049/iet-rpg:20060009.
[19] T. Stetz, K. Diwold, M. Kraiczy, D. Geibel, S. Schmidt, M. Braun, Techno-economic assessment of voltage control strategies in low voltage grids, IEEE Trans. Smart Grid 5 (2014) 2125–2132, https://doi.org/10.1109/TSG.2014.2320813.
[20] S.M. Ismael, S.H.E. Abdel Aleem, A.Y. Abdelaziz, A.F. Zobaa, State-of-the-art of hosting capacity in modern power systems with distributed generation, Renew. Energy 130 (2019) 1002–1020, https://doi.org/10.1016/J.RENENE.2018.07.008.
[21] P. Chaudhary, M. Rizwan, Voltage regulation mitigation techniques in distribution system with high PV penetration: a review, Renew. Sustain. Energy Rev. 82 (2018) 3279–3287, https://doi.org/10.1016/J.RSER.2017.10.017.
[22] A. Ballanti, L.F. Ochoa, On the integrated PV hosting capacity of MV and LV distribution networks, in: 2015 IEEE PES Innovative Smart Grid Technologies Latin America (ISGT LATAM), 2015, pp. 366–370, https://doi.org/10.1109/ISGT-LA.2015.7381183.
[23] Z. Wang, G. Yang, Static operational impacts of residential solar PV plants on the medium voltage distribution grids—a case study based on the Danish Island Bornholm, Energies 12 (2019), https://doi.org/10.3390/en12081458.
[24] B.B. Navarro, M.M. Navarro, A comprehensive solar PV hosting capacity in MV and LV radial distribution networks, in: 2017 IEEE PES Innovative Smart Grid Technologies Conference Europe (ISGT-Europe), 2017, pp. 1–6, https://doi.org/10.1109/ISGTEurope.2017.8260210.
[25] CENELEC, EN 50160:2010, (2010). https://www.cenelec.eu/dyn/www/f?p=104:110:1364914901600001::::FSP_ORG_ID,FSP_PROJECT,FSP_LANG_ID:1258595,51993,25 (accessed September 25, 2020).
[26] Energimarknadsinspektionen, Energimarknadsinspektionens Författningssamling [Statutes of the Swedish Energy Markets Inspectorate], 2013, pp. 1–8.
[27] DIN-VDE, VDE-AR-N 4105: Power Generation Systems Connected to the Low-Voltage, Distribution Network, 2011.
[28] UK Parliment, The Electricity Safety, Quality and Continuity Regulations 2002, 2002. https://www.legislation.gov.uk/uksi/2002/2665. (Accessed 25 September 2020).
[29] M.H.J. Bollen, P. Verde, A framework for regulation of RMS voltage and short-duration under and overvoltages, IEEE Trans. Power Deliv. 23 (2008) 2105–2112, https://doi.org/10.1109/TPWRD.2008.919191.
[30] M. Hyvärinen, Electrical Networks and Economies of Load Density, Helsinki University of Technology, 2008.
[31] E. Nyholm, M. Odenberger, F. Johnsson, An economic assessment of distributed solar PV generation in Sweden from a consumer perspective – the impact of demand response, Renew. Energy 108 (2017) 169–178, https://doi.org/10.1016/J.RENENE.2017.02.050.
[32] N. Shemsedin, Planning and Operation of Large Amounts of Wind Power in a Distribution System, Chalmers, 2015.
[33] C. Barteczko-Hibbert, After Diversity Maximum Demand (ADMD) Report, 2015. http://www.networkrevolution.co.uk/wp-content/uploads/2015/02/After-Diversity-Maximum-Demand-Insight-Report.pdf.
[34] VDI, VDI 4655: Reference Load Profiles of Single-Family and Multi-Family Houses for the Use of CHP Systems, Düsseldorf, 2008.
[35] H. Ruf, Limitations for the feed-in power of residential photovoltaic systems in Germany – an overview of the regulatory framework, Sol. Energy 159 (2018) 588–600, https://doi.org/10.1016/J.SOLENER.2017.10.072.
[36] M. Zain ul Abideen, O. Ellabban, L. Al-Fagih, A review of the tools and methods for distribution networks' hosting capacity calculation, Energies 13 (2020) 2758, https://doi.org/10.3390/en13112758.
[37] Z. Norwood, E. Nyholm, T. Otanicar, F. Johnsson, A geospatial comparison of distributed solar heat and power in Europe and the US, PLoS One 9 (2014), e112442, https://doi.org/10.1371/journal.pone.0112442.
[38] J.P. Zimmerman, End-use Metering Campaign in 400 Households in Sweden Assessment of the Potential Electricity Savings, Eskilstuna, 2009. https://www.energimyndigheten.se/globalassets/statistik/festis/elmatning-i-bostader/final_report.pdf.
[39] Svenska Elektriska Kommissionen, SS 424 14 06 (Methods of Calculation to Safeguard Correct Disconnection – Single Cable in a Directly Earthed System Protected by Fuses (Simplified Method)), 2005.
[40] Eurostat, 2011 Census, 2011. https://ec.europa.eu/CensusHub2. (Accessed 28 March 2019).
[41] Statistics Sweden, Population Density, Geodata Statistics, 2018. https://www.scb.se/hitta-statistik/regional-statistik-och-kartor/geodata/oppna-geodata/statistik-pa-rutor/. (Accessed 26 April 2019).
[42] VDE, DIN VDE 0100-410, Berlin, Germany, 2018.
[43] Eurostat, GEOSTAT Population Grid, 2011. https://ec.europa.eu/eurostat/web/gisco/geodata/reference-data/population-distribution-demography/geostat. (Accessed 25 September 2020).
[44] D. Murray, L. Stankovic, V. Stankovic, An electrical load measurements dataset of United Kingdom households from a two-year longitudinal study, Scientific Data 4 (2017) 160122, https://doi.org/10.1038/sdata.2016.122.
[45] IET, Requirements for Electrical Installations - BS7671, 2018.
[46] V. Rigoni, L.F. Ochoa, G. Chicco, A. Navarro-Espinosa, T. Gozel, Representative residential LV feeders: a case study for the North West of England, in: 2016 IEEE Power and Energy Society General Meeting (PESGM), 2016, p. 1, https://doi.org/10.1109/PESGM.2016.7741222.
[47] European Parliment, Commission Delegated Regulation 2019/1755, 2019. http://data.europa.eu/eli/reg_del/2019/1755/oj. (Accessed 25 September 2020).
[48] G. Kerber, Aufnahmefähigkeit von Niederspannungsverteilnetzen für die Einspeisung aus Photovoltaikkleinanlagen, Technical University of Munich, 2011.
[49] Eurostat, Energy Consumption in Households, 2019. https://ec.europa.eu/eurostat/statistics-explained/index.php/Energy_consumption_in_households#Energy_consumption_in_households_by_type_of_end-use. (Accessed 17 September 2020).
[50] P. Zetterström, Utökade dimensioneringskrav från en förhöjd installationsgrad av distribuerade solcellssystem, Uppsala University, 2016. http://uu.diva-portal.org/smash/get/diva2:938768/FULLTEXT01.pdf.
[51] N. Berg, S. Estenlund, Solceller I Elnät Betydande Andel Solcellers Inverkan På Lågspänningsnätet, Lund University, 2013.
[52] P.B. Kitworawut, D.T. Azuatalam, A.J. Collin, An investigation into the technical impacts of microgeneration on UK-type LV distribution networks, in: 2016

Australasian Universities Power Engineering Conference (AUPEC), 2016, pp. 1–5, https://doi.org/10.1109/AUPEC.2016.7749321.
[53] S. Bhagavathy, N. Pearsall, G. Putrus, S. Walker, Performance assessment of a three-phase distribution network with multiple residential single-phase PV systems, CIRED - Open Access Proc. J. 2017 (2017) 2480–2483, https://doi.org/10.1049/oap-cired.2017.0805.
[54] F. Ebe, B. Idlbi, J. Morris, G. Heilscher, F. Meier, Evaluation of PV hosting capacity of distribuion grids considering a solar roof potential analysis — comparison of different algorithms, in: 2017 IEEE Manchester PowerTech, 2017, pp. 1–6, https://doi.org/10.1109/PTC.2017.7981017.
[55] L. Hülsmann, Evaluation of Two Distribution Grids in Terms of PV Penetration Limits and Effectiveness of Reactive Power Controls, Royal Institute of Technology, 2016.
[56] F. Carigiet, M. Niedrist, C. Scheuermann, F. Baumgartner, Case study of a low-voltage distribution grid with high PV penetration in Germany and simulation analyses of cost-effective measures, in: 31st European Photovoltaic Solar Energy Conference and Exhibition, Hamburg, 2015.
[57] UK Power and Networks, Design and Planning: Framework for Underground Networks in UK Power Networks, 2011. https://www.ukpowernetworks.co.uk/internet/asset/3de30a5b-8ab2-42db-95a4-994a5ce5f0b7/UKPN_G81_Design_Planning_Appendix_v1.0_kk_040711.pdf. (Accessed 25 September 2020).
[58] Statistics Sweden, Antal Personer Per Hushåll Efter Region Och Boendeform, 2018. http://www.statistikdatabasen.scb.se/pxweb/sv/ssd/START__HE__HE0111/HushallT29/. (Accessed 17 September 2020).
[59] I.U.D. Igor Satori, Joana Ortiz, Jaune Salom, Estimation of load and generation peaks in residential neighbourhoods with BIPV: bottom-up simulations vs. Velander, in: World Sustainable Building, Barcelona 3, 2014.
[60] Office for National Statistics, Families and Households in the UK: 2019, 2019. https://www.ons.gov.uk/peoplepopulationandcommunity/birthsdeathsandmarriages/families/bulletins/familiesandhouseholds/2019. (Accessed 25 September 2020).
[61] Eurostat, Household Composition Statistics, 2019. https://ec.europa.eu/eurostat/statistics-explained/index.php/Household_composition_statistics. (Accessed 17 September 2020).